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What Does an Observed Atom Reveal to Its Observer?*

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Abstract—The acts of measurement, even unless intervening with the quantum object, impede the object's evolution. This "quantum Zeno" effect has been contemplated for decades. An experimental demonstration had been attempted that applied a series of light pulses during the microwave-induced evolution of an ensemble of trapped ions, followed by measurement of the ensemble's state. The results completely agreed with quantum-mechanical predictions. However, the impediment of the quantum evolution *by measurement* cannot, *in principle*, be verified on an ensemble, since such an experiment yields, as the result, an expectation value, not an eigenvalue, and the micro-state of the system is not revealed by the measurement. Moreover, each radiative intervention requires subsequent detection of the emerging state in order to qualify as a measurement. A recent experiment used a *single* quantum system and has included repeatedly *probing* the state of the system—not just pulsed irradiation—alternating with the laser-driven evolution. Here, each measurement signals the micro-state of the system. The statistics of *correlated* results reveals the inhibiting effect of reiterated measurements on the microscopic system. The coherent laser excitation of the ion amounts to the implementation of the Hadamard transformation ("one-qubit quantum logic gate"), on an *electronic* resonance, important for application in quantum information processing by individually addressable atoms. Also, an ion has been coherently driven on the ground-state *hyperfine transition* by a microwave. In this system, which lacks intrinsic relaxation, again the impediment of the ion's evolution by repeated measurements was demonstrated.

1. INTRODUCTION

The evolution of quantum mechanics—we have just recently commemorated its seventy-fifth anniversary—has been profoundly shaped by the formulation and critical evaluation of what is called "Gedanken" experiments. Only recently, the development of novel technical means has allowed us to transpose some of these Gedanken experiments into reality: Examples for such an achievement are the storage, laser cooling, and laser addressing of individual ions in electromagnetic or electrodynamic ion cages or "traps," a technique pioneered 20 years ago [1], or the manufacturing of highly coherent light sources [2]. Another instrumental example is microwave resonators that are designed to interact with single atoms [3]. These and other achievements have, on one hand, allowed physicists to implement experiments that have stimulated refinements of the concepts, on the other hand, enabled them to make unexpected observations, as, e.g., the direct observation of Bohr's quantum jumps some years ago [4, 5].

The problems that mark the revived debate on the foundations and the interpretation of quantum mechanics include in particular

(1) the temporal evolution of quantum-mechanical systems,

(2) the quantum-mechanical measurement, and

(3) the emergence of the classical world out of the quantum micro-cosmos.

Here, we report about considerations on hypothetical experiments, and on the results of two real experiments upon a subject that concerns these problems, and that has been contemplated for about half a century. This subject is the temporal evolution of a quantum system *under continuous or repeated observation*. It has been recognized long ago that the evolution of such a system along a particular degree of freedom must become frustrated by measurements of the corresponding observable [6, 7]. This consequence has been quoted the "Quantum Zeno Effect" [8], and many conceptual and interpretative ideas have contributed to an immense body of disputed material—see the work of Beige and Hegerfeldt [9], of Home and Whitaker [10], and references therein. In contrast, there are only very few reported experiments that claim real demonstration of the effect [11, 12].

2. CLASSICAL AND QUANTUM ZENO EFFECTS

In order to put the problem in convenient perspective, let us start with a kind of classical analogue. A beam of monochromatic linearly polarized light (polarization vector $\mathbf{P}_0$) is supposed to propagate through a polarization-rotating sugar solution. After the path length L, the polarization has rotated by the angle θ

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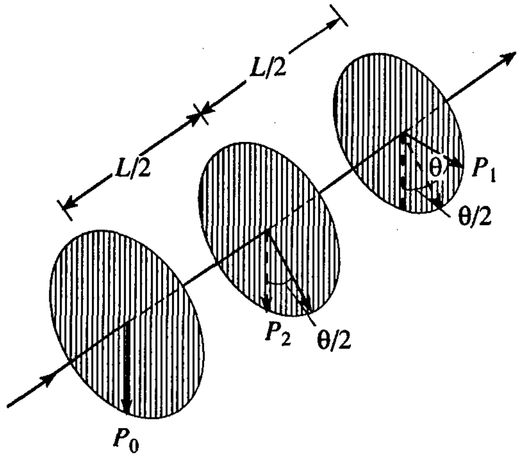

Fig. 1. A light beam of polarization P_0 propagates through a polarization-rotating medium. After path length L, the polarization is P_1, rotated by the angle θ. With a second analyzer inserted at $L/2$, the final rotation is θ/2.

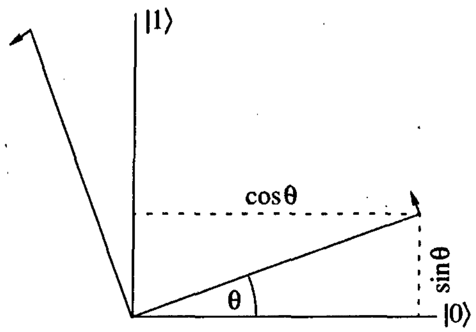

Fig. 2. 2D configuration space.

to the direction $\mathbf{P}_1$, as may be proven by a rotatable analyzer filter. When one inserts a second analyzer halfway along L, at $L/2$, whose direction of transmittance $\mathbf{P}_2$ is set parallel to the initial light polarization $\mathbf{P}_0$, the final angle of rotation will have diminished to θ/2 (Fig. 1). Moreover, the light amplitude will turn out reduced, too, since the intermediate analyzer 2 projects the light to its original direction of polarization, $\mathbf{P}_0$. Insertion of n intermediate analyzers at equal distances L/n from each other leaves the total angle of polarization rotation θ/n. Since the projective loss per analyzer, i.e., per "measurement" of polarization, is approximately θ^2/n^2, the total loss turns out θ^2/n. In the limit of large n, both the total rotation and the total loss vanish—the angular evolution of polarization has become impeded.

A two-level quantum system, say an atom, whose Bohr resonance is driven by monochromatic resonant radiation shares certain elements of symmetry with light polarization. The transition probability, from the initially prepared state 0 to the other state 1, under the action of a driving pulse of radiation with duration T and small "area" $\theta = \Omega T$, is

$$P_{01}(1) = \sin^2\theta \cong \Omega^2 T^2, \qquad (1)$$

where Ω is the Rabi frequency of the driving radiation at the location of the atom (Fig. 2). The argument "1" indicates final probing of the system, e.g., by one laser pulse tuned to a resonance line that is capable of eliciting a reaction from the system—resonant scattering, e.g.—*only* if the system is found in one particular state, say, in the lower one. Now let $n - 1$ additional short probe pulses be applied to the system that are temporally separated from each other by intervals $\tau = T/n$. Since everyone of these pulses "projects" the system into state 0 or 1, the net transition probability turns out

$$P_{01}(n) \cong \Omega^2 \tau^2 n = \Omega^2 T^2/n, \qquad (2)$$

which approaches zero upon n growing: the system seems to stick to its initial state [13].

3. A PREVIOUS ATTEMPT

Along the above lines, an experiment had been performed on a quantum system that consisted of a magnetic resonance of 5000 Be^+ ions stored in an electromagnetic ("Penning") trap [11]. The resonance between the two hyperfine-split levels of the ions' electronic ground state was driven by a resonant microwave, and the lower one of the two was probed by laser pulses exciting resonance fluorescence to become detected. It is not surprising that the results of this experiment turned out in complete agreement with the predictions of quantum mechanics.

This experiment has aroused a wealth of comments and criticism over the past years: Some of these comments centered around the application of projection postulate and state reduction. Since a model that takes full account of three levels, two transitions, and two resonant fields describes correctly all details of the dynamics of the system, the interpretation of the inhibition of evolution as a consequence of state reduction was said inadequate, and the effect claimed unrelated with measurement. Others objected the interpretation as QZE being inadequate since state reduction was *not* required! Recently Beige and Hegerfeldt have clarified this point [9]. They showed that state reduction is a global way of taking into account the parts of a system *not* explicitly modelled. They estimated the errors of the assumption of state reduction and proved that, in most situations, this approximation is very precise. Consequently, acceptance or nonacceptance of state reduction is irrelevant for the Zeno problem [10].

More to the point seem other objections: In the experiment, the state of the system was probed only *after* that the series of pulsed interventions by the light had happened. Thus, only *net* probabilities of the system staying in the same eigenstate, or moving to the

other state, could be recorded. Back-and-forth transitions of individual members, as well as correlated up-down transitions of pairs of ions went unnoticed [14]. Moreover, Home and Whitaker have pointed out that the genuine QZE (or Zeno "paradox") is not supposed to consist in a dynamic interaction of system and meter: It must represent a *non-local* effect derived from a *null* result [10]. However, such an effect is indistinguishable, in principle, from a dynamic effect *unless* the system is an *individual quantum object* [15–17].

In order to look on these arguments more closely, let us turn back to the states of polarized light. The complete set of these states may be represented by the unit sphere (Fig. 3): States of complete polarization cover the surface of this "Poincaré sphere." Orthogonal states of linear polarization are placed at the poles, states of elliptical and circular polarization at the equator including the degenerate cases of linear polarization at $\pm\pi/4$. States of partial polarization fill the interior of the sphere. A two-level quantum system obeys SU(2) symmetry [18] and is represented in a similar way. In fact, the two representations are said "locally isomorphic" [19]. Pure states are localized on the surface, and the two eigenstates, say, of energy, on the poles (Fig. 4). Coherently exciting the system by a radiative pulse of area θ may generate the superposition state P_1, provided that no uncontrolled interaction among the constituents of the system, with the meter, or with the environment takes place. Such an interaction would give rise to decoherence of the system, represented by a move of the state vector to the interior of the sphere. In particular, mere *dephasing* of the system's wave function would leave the state vector with same projection on the z-axis as before. A measurement on a system made up of a—large enough—ensemble of quantum objects always yields a result very close to the expectation value predicted by quantum mechanics: this measurement is approximately deterministic. The small deviation from the quantum-mechanical expectation value, the "projection noise" [20, 21], decreases with the number of members of the ensemble increasing. Thus, the measurement does not discriminate a pure state from a mixed one being measured. In contrast, an individual quantum object warrants a pure state to exist prior to the measurement, provided that the interaction with the driving radiation is coherent. Moreover, it allows *two* potential outcomes of a measurement, the eigenvalues 0 or 1, one of which turns actual. The potential results are stochastically distributed, but their likelihood is weighted according to the preceding preparation of the state. Consequently, the effect of a measurement cannot be mixed up with physical intervention by neighboring quantum objects, radiative fluctuations, environment, or meter, whatsoever.

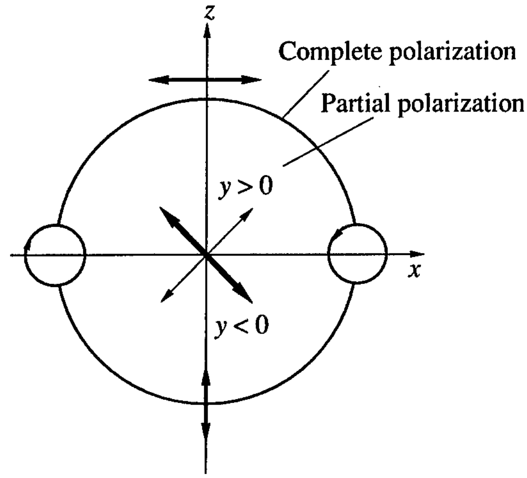

Fig. 3. Configuration space of light polarization ("Poincare sphere"). Thick arrow foreground, thin arrow background.

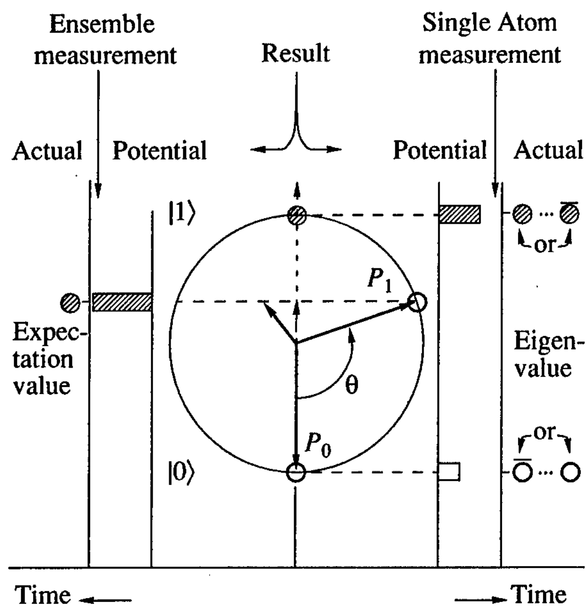

Fig. 4. Preparation and measurement of 2-level quantum system (SU2). P_0 initial state vector, P_1 after preparation of single quantum system (right), or ensemble (left).

4. TEST ON A SINGLE QUANTUM SYSTEM

In fact, the intention of demonstrating the effect of a *measurement* and discriminating it from the effects of dephasing the wave function requires one to apply this measurement on an *individual* quantum system. We may try to identify more of the particular features that discriminate an individual quantum object from an ensemble, and to correlate those peculiarities with potential applications:

(i) Lacking interaction with neighboring systems has been recognized as a critical feature for the application of single ions (or atoms) as a frequency standard

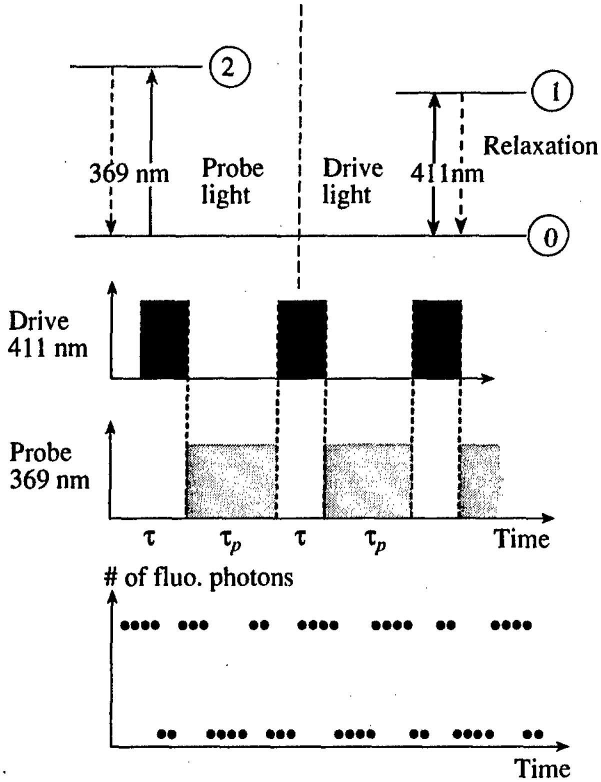

Fig. 5. Alternating opto-optical double resonance: Scheme of levels and excitation of $^{172}Yb^+$ (top). Temporal schedule (middle). Schematic trajectory of results (bottom).

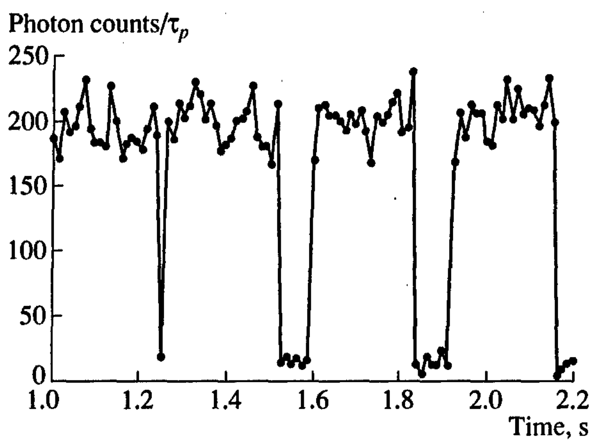

Fig. 6. Trajectory of recorded data: The results "probe scattering on" and "off" form alternating sequences of quasi-random length.

[22]. (ii) As outlined above, only a single quantum system reveals its micro-state with the measurement. This fact makes single system applicable for quantum information processing [23]. (iii) Finally, the stochastic character of the result of a measurement leaves the individual addressing of quantum systems suitable for applications as in cryptography [24].

For an unequivocal proof of the inhibition of quantum evolution by *measurement* in contrast with external physical intervention, not only a demonstration on an individual quantum system is indispensable, but the measurement should be capable of proving the *absence* of such external intervention. An individual system that satisfies this requirement is a single ion with an unpaired electron, stored in an electrodynamic trap and laser-cooled, that may be pulse-excited, on a narrow resonance, by a quasi-monochromatic laser. An example is the dipole-forbidden $S_{1/2}$–$D_{5/2}$ line of a Ba^+ or Yb^+ ion. Alternating resonant probe pulses of laser light may or may not excite fluorescence on the $S_{1/2}$–$P_{1/2}$ resonance line, depending on the preceding attempt of excitation being successful, or not: The appearance of a detector signal from this scattered light proves the ion to be found in the $S_{1/2}$ state, its absence makes the ion found in the $D_{5/2}$ state (Fig. 5) [25]. The combination of a drive pulse and a probe pulse amounts to preparation and measurement of the ion's internal state; two successive measurements whose results differ signal the ion to have undergone a transition—either an absorptive, or an emittive one. Trajectories formed by the bimodal results of many measurements, as schematically shown in the bottom part of Fig. 5, consist of two alternating kinds of "waiting intervals" made up of equal results, namely those with scattering either "on," or "off," whose lengths look random. However, the statistical distributions of the sequences of equal results that appear in these intervals embody the evolution of the driven quantum system, on the energy coordinate of configuration space, in the presence of the reiterated interventions by the probe light. An experiment along these lines has been implemented recently, making use of an individual trapped and laser-cooled $^{172}Yb^+$ ion [26]. An actual trajectory of corresponding results is shown in Fig. 6.

The distributions of sequences over their length q are determined by the nutational dynamics of a spin-like quantum system that obeys the SU2 symmetry [17, 27]. With such an object lacking relaxation, the probability of finding this system in the same state as before, $|0\rangle$ or $|1\rangle$, is simply

$$p_0 = p_1 = \cos^2\theta/2, \tag{3}$$

and the transition probability is

$$p_{01} = p_{10} = \sin^2\theta/2, \tag{4}$$

where the "area" of the driving pulses, $\theta = \Omega\tau$, is the product of the Rabi frequency Ω and pulse duration τ. The probability of q successive equal results (all "on," corresponding to the ion being found all the time in state $|0\rangle$, or all "off," corresponding to the ion always in state $|1\rangle$ is

$$U(q) = U(1)V(q-1), \tag{5}$$

where the likeliness of the ion *remaining* in its eigenstate for q subsequent measurements is $V(q) = p_i^q$ (i = 0 or 1), provided that each measurement comes along with a "reduction" of the ion's state, or something of equivalent effect. Let us assume, for the moment, however, this latter assumption to be violated, i.e., the subsequent irradiation by probe light and simultaneous recording of "scattering" or "no scattering" having no effect on the coherent evolution of the ion. Under this condition, V had to be replaced, in Eq. (5), by

$$V_c(q) = \prod_{n=1}^{q} V'(n), \tag{6}$$

where $V'(n) = \cos^2(n\theta/2)$ is the probability of finding the ion, only by the nth next measurement, in the same state as by the first one of the sequence. Examples of the predictions for the distributions of sequences according to Eqs. (3), (5), and (6) are shown in Fig. 7, for two values of the pulse area θ of the radiation, i.e., the nutational phase angle of the driven resonance being small, or large, compared with $\pi/2$. Whereas the distributions calculated according to Eqs. (3) and (5), that take the effect of the observations into account, are purely exponential, the distributions evaluated with Eq. (6) show a step-like shape (for large θ), or a parabolic shape (for small θ) on the logarithmic scale. The important feature is the *qualitative* difference of the distributions V and V_c, that allows one to discriminate the two reciprocally exclusive conditions by comparison with the experimental results.

For quantitative evaluation of the data from the experiment on $^{172}Yb^+$, some modifications of the above simple model are required. The upper state of the driven resonance ($D_{5/2}$) is metastable; its lifetime is 5.7 ms. The lower state $S_{1/2}$ is probed by attempts of exciting resonance scattering by laser light of 367 nm wavelength. The driving radiation, light of 411 nm wavelength, is generated by a frequency-doubled and controlled diode laser and is highly monochromatic. Notwithstanding energy and phase relaxation being minute, these effects have to be included with quantitative modelling [26]. For this purpose, a closed solution of the Bloch equations on resonance has been used [28]. The "on" and "off" distributions no longer agree. Phases of nutation have been derived fitting θ in Eq. (5) to each experimental distribution, and taking into account the level degeneracy. By the value of phase relaxation derived from the fit one concludes that the mean phase diffusion of the driving light per driving pulse duration τ = 2 ms is less than 25 Hz. Also, a correction to the above model is required that takes into account the finite length of the trajectories. It shows up as a slight deficiency in the distributions, as compared with an exponential that is predicted for long sequences ($q \gg 1$).

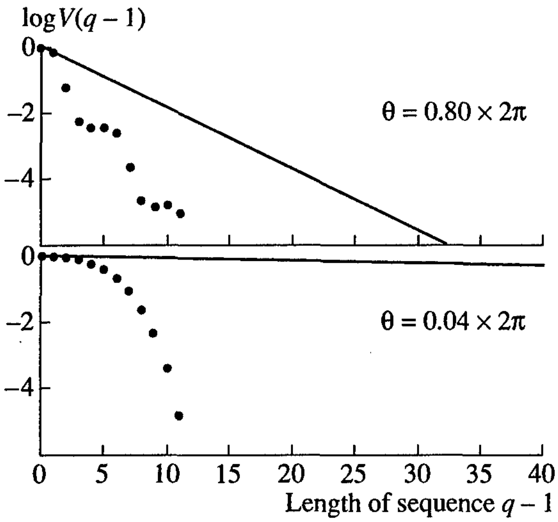

Fig. 7. Statistical distributions of sequences, vs. their length, as calculated with the state-reducing effect of the measurements included (V, lines) or ignored (V_c, dots). $\theta > \pi$ (top), $\theta \ll \pi$ (bottom).

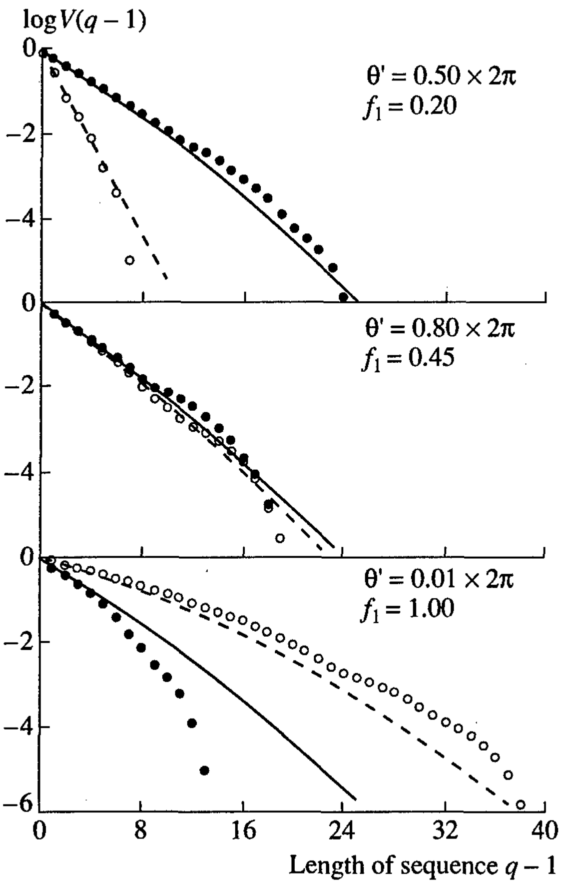

Fig. 8. Probability $U(q)/U(1)$ of uninterrupted sequences of q "on" results (white dots) and "off" results (black dots). The lines show the distributions of probabilities $V(q-1)$ for the ion's evolution on its drive transition, according to Eqs. (3) and (5). θ' and f_1 from fit: values $f_1 < 1$ indicate redistribution, over sublevels, by cycles of spontaneous decay and reexcitation. From [26].

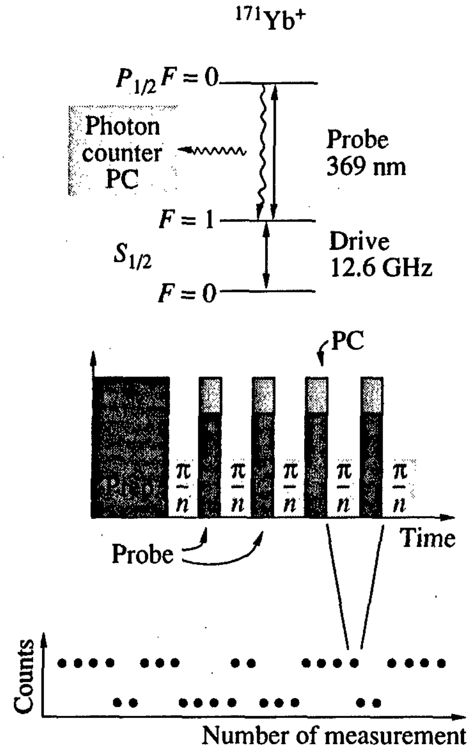

Fig. 9. Alternating double resonance on individual $^{171}Yb^+$ ion: Scheme of excitation and detection (top), temporal strategy of measurements (middle), trajectory of results (bottom).

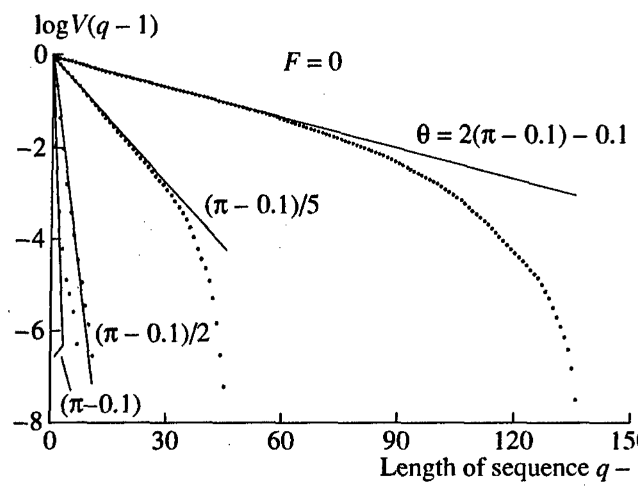

Fig. 10. Probability $U(q)/U(1)$ of uninterrupted sequences of results "scattering off" (dots). Distributions of probabilities $V(q-1)$, vs. $q-1$, calculated with Eqs. (3) and (5) (lines). Phase values θ set to fit observed data.

A set of distributions of recorded "on" and "off" sequences, $U(q)/U(1)$, is shown in Fig. 8, for three values of the fractional phase, $\theta' = 0 \bmod 2\pi$. Moreover, the fitted model distributions are shown. Unlike with a measurement on an ensemble of *quantum objects*, the present ensemble of *measurements* provides the observer with detailed knowledge of the micro-state. The data demonstrate that in fact after preparing the ion in a superposition state, it is found in one of its eigenstates upon each observation. A crucial point is whether this finding results from physical intervention, by the environment or the meter, into the quantum system, or just from the gain of information that the observer extracts from the measurement. The former alternative is disproven by the very conditions of the actual quantum object, namely the driven ionic quadrupole, in the experiment: (i) There is no energy dissipation, except for that of the light scattered off the laser beam and being detected. (ii) Almost no phase perturbation is inflicted upon the quantum object's wave function, since the phase of the driving light shows a standard variation much smaller than 2π during a pulse, and the upper state's lifetime is long enough. (iii) There is no radiative recoil upon the ion from the *drive* radiation, since the prevailing "strong" trapping regime (linewidth $\Delta\omega \gg$ vibrational frequency ω_v) makes the trap pick up the recoil [29]. This is not so, in the reported experiment, with the excitation of fluorescence by the probe light, i.e., in the "on" sequences. However, even there, an estimate shows that the transfer of momentum between light and ion is quite insufficient for a modification of the ion state equivalent to state reduction [30]. On the other hand, measurements whose results are "off" completely lack transfer of recoil, since no interaction of ion and light has happened at all. Indeed, this kind of conditions justify to consider the pertaining observations as "quantum non-demolition" measurements [17].

5. A RELAXATION-FREE VERSION

An alternative demonstration of the measurement-imposed impediment of the ion's quantum evolution has made use of the microwave-driven ground-state hyperfine resonance of a $^{171}Yb^+$ ion as a relaxation-free quantum object (Fig. 9, top) [31]. Here, the upper one of the hyperfinesplit ground state components, $F = 1$, was monitored by laser pulses of 367 nm wavelength, also tuned to the ion's $S_{1/2}$–$P_{1/2}$ resonance line. If the ion, initially pumped to its $F = 0$ ground-state component, was taken to its $F = 1$ state in the course of the coherent preparation of a superposition state by the driving micro-wave pulse and subsequently excited by the applied probe light, a burst of light scattered off the ion and was recorded by the photon counting device. Here, the lack of scattering signaled *missing* excitation to the $F = 1$ state, i.e., the ion having remained in its $F = 0$ state. This scheme intrinsically lacks relaxation and decoherence, in view of the practically infinite lifetime of the $F = 1$ state, and the negligible level of phase noise on the micro-wave. Thus, measurements whose result is "off" may be fully analyzed in terms of the simplest model outlined above, neglecting relaxation. On the other hand, when an "on" signal is observed, the laser excitation of the ion's $F = 1$, $m_F = 0$ state gives rise to

optical pumping into the $m_F = \pm 1$ Zeeman levels. Thus, the evaluation of the "on" sequences in the trajectories requires more complex modelling.

The $^{171}Yb^+$ ion was localized in the node of the trapping radio field to less than 10 nm deviation, and cooled by the resonance light of $\lambda = 369$ nm wavelength, downtuned from resonance by some 10 MHz. The ion's residual motional amplitude x was as small as to keep it well inside the Lamb–Dicke regime, $x \ll \lambda$. Resonant excitation ($\omega = \omega_0$) by the microwave radiation was assured by the application of a double-pulse test routine making use of Ramsey's technique [21]: The two pulses were temporally separated by t_0 in the first measurement, and followed by a probe laser pulse. In the subsequent measurements, t_0 was stepwise incremented by $m\delta t$, where $m \leq 50$ is the number of the measurement. Numerous trajectories of 50 measurements each have been accumulated. Ramsey fringes that emerge from these data indicate spurious differential precession of the ion's spin in the rotating frame of the microwave, and reveal the concomitant residual detuning of the microwave from the ion's hyperfine resonance, that is being eliminated. Series of single pulses incremented in power or length and separated by probe pulses served for the precise setting of the angle of nutation, i.e., of the pulse area, $\theta = \Omega\tau$.

In the actual measurements, after an initial laser pulse that pumped the ion into its $F = 0$ groundstate, trains of n resonant microwave pulses with well-defined pulse area $\theta = \pi/n$ irradiated the ion, where n is a small integer. Note that, in contrast with laser light, the microwave allows one to *preset* θ, even to a fraction of π. The pulses alternated with laser probe pulses, part of whose light scattered off the ion and was detected by the photon counting device gated open in synchronism with the probe pulses (Fig. 9, center). A pair made up of a driving pulse and a probe pulse again represents the preparation of a superposition state of the ion's spin, and the quasi-random read-out of one of the pertaining eigenstates. The recorded series of 2000 of these measurements amount to trajectories that consist of waiting intervals formed by equal results that alternate between "on" and "off," from an interval to the next one (Fig. 9, bottom). The distribution $U(q)/U(1)$ of sequences of equal results over their length q has been evaluated and compared with the predictions of Eqs. (1)–(3). This is shown in Fig. 10, for the "off" sequences, where data for nominally $\theta = \pi$, $\pi/2$, $\pi/5$, and $2\pi - 0.1$ are displayed. The lines show calculated values of $V(q - 1)$, with θ fitted in order to match the recorded data. Note that the factual values of the pulse area θ of the microwave drive differ from their nominal pre-set values by some 10%. Very long sequences appear somewhat deficient, i.e., excessive excitation to the $F = 1$ level seems to prevail. This finding is indicative of some dephasing to have happened on a time scale of seconds.

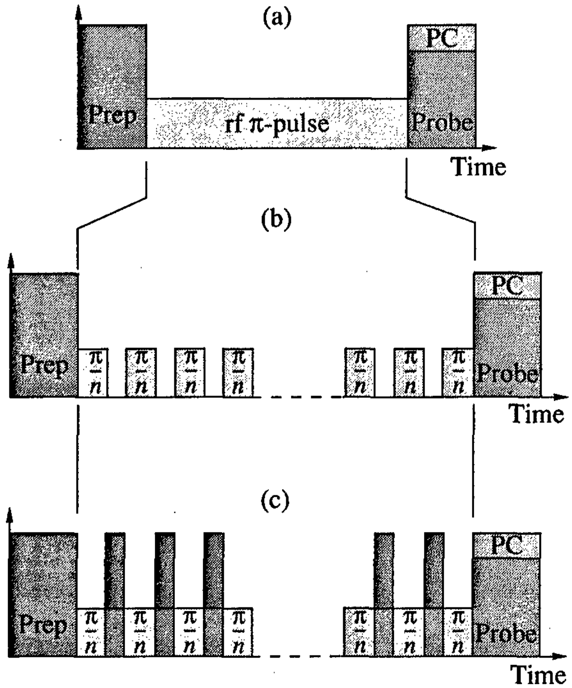

Fig. 11. Alternating double resonance with π-pulse of driving radiation (top). The π-pulse fractionated: No intermediate probing (middle), intermediate pulses of probe light, and simultaneous detection of scattered light (bottom).

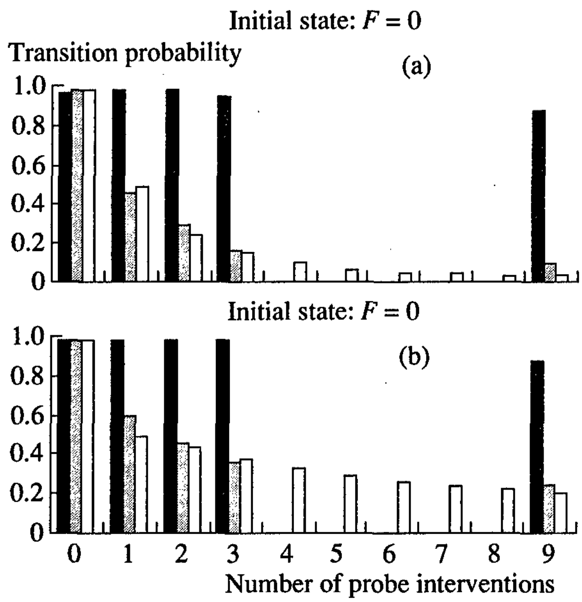

Fig. 12. Transition probability "off" ⟶ "on" with no intermediate probing (dark bars), and with this probing (grey bars), vs. number n of π-pulse partition. The probability is evaluated from a sub-ensemble of measurements that completely lacks "on" results in the $n - 1$ intermediate observations ("selective" measurements). White bars: Transition probability calculated after Eq. (2) (top). Same, but transition probability evaluated from entire ensemble of measurements ("non-selective" measurements). White bars: Transition probability calculated after Eq. (3) (bottom). Driving time is 2.9 ms, probing time is 3 ms. From [31].

An alternative scenario of measurements has included a preparatory laser pulse that pumped the ion into the $F = 0$ ground state, and a series of n driving pulses of area π/n (Fig. 11b). This scheme of driving extends a complete "π flop" to the ion, i.e., deterministic transfer to the $F = 1$ state, under the condition of absent relaxation (Fig. 11a). A final probe pulse must give rise to definitely recording the result "fluorescence on". Then, the ion was irradiated by probe pulses applied *between* the individual π/n driving pulses. The detector of the scattered light was gated on during these intermissions of the drive (Fig. 11c), and the results were recorded- and stored separately from the result of the final detection. Data from 2000 repetitions of these two series of measurements have been recorded. The first set of series—no intermediate probing—is supposed to show unit transition probability. The corresponding results are displayed, vs. n, as dark bars in Fig. 12. Some decoherence makes the transition probability drop from unity by 12% at $n = 9$.

The data of the second set—intermediate probing—have been evaluated in two different ways:

(i) Only those series were taken into account that show an "off" result with everyone of the $n - 1$ intermediate probe excitations. Their fraction with a final "on" result is related to the entire subset of series characterizing a "selective" measurement. Fig. 12a shows the data as grey bars. The corresponding transition probability (white bars) is

$$P_{01}^{(s)} = \sin^2(\pi/2n). \quad (7)$$

This probability may be thought to represent the effect of only the last driving pulse, and the final probing. The statistical distributions of photon counting have been found Poissonian. Thus the errors are dominated by quantum noise. The observed and calculated data agree within this error margin.

(ii) All results of intermediate probing were ignored, and from an *entire* set of series with given n, the fraction of series with final "on" result was related to the total number (Fig. 12b, grey bars). This strategy gives rise to "non-selective" measurements, and the corresponding transition probability is

$$P_{01}^{(n)} = \frac{1}{2}(1 - \cos^n(\pi/n)). \quad (8)$$

Figure 12b shows, as white bars, this transition probability calculated according to Eq. (8). Most of the data agree with the results of the simple model, within the statistical errors.

In principle, also the statistics of "on" sequences may be used for a demonstration of the QZE. However, here, the analogous observations on the ion prepared in state $F = 1$, $m_F = 0$ suffer from optical pumping, by the probe light into the other Zeeman sublevels, such that their interpretation is less straightforward.

6. CONCLUSIONS

An experiment designed for non-selective measurements on an *ensemble* of trapped ions has been reported before [11]. However, its interpretation has been questioned. The reported demonstrations of the QZE on an individual ion are not afflicted by reaction from the meter, they are "quantum non-demolition" measurements [17], and they satisfy the condition of a "nonlocal, null-result" effect [10]. Moreover, since they involve an individual quantum system, their results cannot be ascribed to dephasing of the wave function, but must be attributed to entanglement of quantum object and meter [10]. Consequently, the reported noninvasive experiments even amount to the demonstration of the "quantum Zeno paradox," a term having been reserved for the impeding effect of reaction-free observation on the evolution of a quantum object.

REFERENCES

1. Toschek, P.E., 1982, Atomic Particles in Traps, Les Houches Session 1982, *New Trends in Atomic Physics*, Grynberg, G. and Stora, R., Eds. (Amsterdam: North-Holland), p. 383.
2. 1997, *Exp. Methods Phys. Sci.*, Vol. 29C: *Atomic, Molecular, and Optical Physics: Electromagnetic Radiation*, Dunning, F.B. and Hulet, R.G., Eds. (San Diego: Academic), chapters 3–7.
3. Goy, P., Raimond, J.M., Gross, M., and Haroche, S., 1983, *Phys. Rev. Lett.*, **50**, 1903.
4. Nagourney, W., Sandberg, J., and Dehmelt, H., 1986, *Phys. Rev. Lett.*, **56**, 2797.
5. Sauter, Th., Neuhauser, W., Blatt, R., and Toschek, P.E., 1986, *Phys. Rev. Lett.*, **57**, 1996.
6. Khalfin, L.A., 1968, *Pis'ma Zh. Eksp. Teor. Fiz.*, **8**, 106 [1968, *JETP Lett.*, **8**, 65].
7. Fonda, L., Ghirardi, G.C., Rimini, A., and Weber, T., 1973, *Nuovo Cimento A*, **15**, 689.
8. Misra, B. and Sudarshan, E.C.G., 1977, *J. Math. Phys.* (N.Y.), **18**, 756.
9. Beige, A. and Hegerfeldt, G.C., 1996, *Phys. Rev. A*, **53**, 53.
10. Home, D. and Whitaker, M.A.B., 1997, *Ann. Phys.* (N.Y.), **258**, 237.
11. Itano, W.M., Heinzen, D.J., Bollinger, J.J., and Wineland, D.J., 1990, *Phys. Rev. A*, **41**, 2295; 1991, *Phys. Rev. A*, **43**, 5168.
12. Kwiat, P., Weinfurter, H., Herzog, T., Zeilinger, A., and Kasevich, M.A., 1995, *Phys. Rev. Lett.*, **74**, 4763.
13. Cook, R., 1988, *Phys. Scr., T*, **21**, 49.
14. Nakazato, H., Namiki, M., Pascazio, S., and Rauch, H., 1996, *Phys. Lett. A*, **217**, 203.
15. Spiller, T.P., 1994, *Phys. Lett. A*, **192**, 163.
16. Alter, O. and Yamamoto, Y., 1997, *Phys. Rev. A*, **55**, 2499.

17. Braginsky, V.B. and Khalili, F.Ya., 1992, *Quantum Measurement* (Cambridge, MA: Cambridge Univ. Press).

18. Feynman, R.P., Vernon, F.L., Jr., and Hellwarth, R.W., 1957, *J. Appl. Phys.*, **28**, 49.

19. Sakurai, J.J., 1985, *Modern Quantum Mechanics* (Menlo Park: Benjamin/Cummings).

20. Wineland, D.J., Bollinger, J.J., Itano, W.M., and Heinzen, D.J., 1994, *Phys. Rev. A*, **50**, 67.

21. Huesmann, R., Balzer, Ch., Courteille, Ph., Neuhauser, W., and Toschek, P.E., 1999, *Phys. Rev. Lett.*, **82**, 1611.

22. See, e.g., 1996, *Proceedings of the 5th Symposium on Frequency Standards and Metrology*, 1995, Woods Hole, MA, Bergquist, J.C., Ed. (Singapore: World Sci.).

23. See, e.g., Steane, A., 1997, *Appl. Phys. B*, **64**, 623.

24. See, e.g., Zbinden, H., Bechmann-Pasquinucci, H., Gisin, N., and Ribordy, G., 1998, *Appl. Phys. B*, **67**, 743.

25. Appasamy, B., Siemers, I., Stalgies, Y., Eschner, J., Blatt, R., Neuhauser, W., and Toschek, P.E., 1995, *Appl. Phys. B*, **60**, 473.

26. Balzer, Ch., Huesmann, R., Neuhauser, W., and Toschek, P.E., 2000, *Opt. Commun.*, **180**, 115.

27. Allen, L. and Eberly, J.H., 1975, *Optical Resonance and Two-Level Atoms* (New York: Wiley).

28. Torrey, H.C., 1949, *Phys. Rev.*, **76**, 1059.

29. See, e.g., Stenholm, S., 1988, *Phys. Scr., T*, **22**, 69.

30. Toschek, P.E. and Wunderlich, Ch., 2001, *Eur. Phys. J. D*, **14**, 387.

31. Balzer, Chr., Hannemann, Th., Wunderlich, Chr., Neuhauser, W., and Toschek, P.E., A Relaxationless Demonstration of the Quantum Zeno Paradox on an Individual Atom (in press).